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Essential Limitations to Signal Detection and Estimation: An Application to the Arctic Under Ice Environmental Noise Problem

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Preface

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ESSENTIAL LIMITATIONS TO SIGNAL DETECTION AND ESTIMATION:
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ABSTRACT

A method to remove narrowband interference in the frequency domain is considered. It consists of first transforming the data into the frequency domain by an FFT, passing the transformed data through an ideal non-linearity, and then transforming the data back into the time domain by an IFFT. The essential mathematical details of the method are given and an error criterion is defined which measures the effectiveness of the technique.

INTRODUCTION

It has been observed that Arctic under ice noise is at times composed of narrowband components [1]. The narrowband noise is primarily due to rubbing ice flows but possibly acoustic dispersion contributes to this phenomenon. This type of interference can significantly degrade the performance of systems which estimate autocorrelation functions to obtain bearing and range information. The data were collected as part of the 1980 Arctic Ocean experiments [2]. A typical sample of Arctic under ice narrowband interference is shown in Figure 1. The data below 2 kHz is broadband noise. But a narrowband component is present in the figure above 2 kHz which lasts for 12.8 seconds.

Many segments of Arctic under ice data contained these highly dynamic narrowband components as shown in Figure 1. The statistical behavior of the dynamic narrowband frequency components were measured by first transforming the data into the frequency domain using a fast Fourier transform (FFT). Then the Kurtosis was estimated for each real and imaginary part of each frequency component over the band for a group of consecutive FFT segments. This procedure is called frequency domain Kurtosis (FDK) estimation [3]. Thus, the FDK estimates the distribution over a time interval consisting of many FFT segments for each real and imaginary frequency component. Many of the Arctic data segments showed non-Gaussian components in the frequency domain based on the FDK estimate. This was due mainly to the highly dynamic nature of the narrowband ice components. Therefore, the FDK is a method whereby the desired signal can be distinguished from the unwanted ice sound.

Once the narrowband interference is identified it can be removed by passing the data of that frequency component through a non-linearity [1]. The output data with the interferring component removed may then be transformed back into the time domain for further processing. For example, the autocorrelation function of the desired signal may be estimated free of the interferring narrowband noise. Or, for two channels, the cross-correlation function may be estimated after both channels are processed through the non-linearity in the frequency domain. The smoothed coherence transform

(SCOT) introduced by Carter, Nuttall, and Cable [4], is a technique which improves time delay estimation between broadband correlated signals in the presence of strong narrowband interference. The SCOT utilizes a frequency domain whitening process of the cross-spectrum. The SCOT processed data is then transformed into the time domain so that time delay can be estimated. Hassab and Baucher [5] have utilized other window functions to improve SCOT performance for signal and noise with smooth spectra.

In contrast to the SCOT and its generalizations, the method of this paper is applied to one channel, or in multichannel cases, to each channel separately. Also, the narrowband interference is removed by passing the frequency domain data through a non-linearity in contrast to whitening. Therefore, only those frequency components that are deemed interference by the FDK estimate are removed. In addition, the optimum non-linearity can be derived from a likelihood ratio formulation under the assumption of independent observations [1].

Time domain techniques may also be employed. For example, data adaptive signal estimation by singular decomposition has been proposed and evaluated in reference 6, which could be used to estimate and remove the interferring components.

In the next section an ideal non-linearity (INL) will be utilized so that the essential mathematical features of the method can be discussed conveniently. However, the INL is similar to the non-linearity discussed in reference 1.

It will also be clear from the following development that the method can also be applied to the spatial domain as well as the frequency domain. But, the discussion will only be concerned with the frequency domain.

THE IDEAL NON-LINEARITY

Let $x(i)$, $i = 0, 1, 2, \ldots, N - 1$, represent the real discrete data. The discrete Fourier transform (DFT) of $x(i)$ is

$$X(k) = \sqrt{1/N} \sum_{i = 0}^{N - 1} w(i) \, x(i) \, \exp(-j2\pi k i/N) \quad ,$$

where, $j = \sqrt{-1}$, and $k = 0, 1, 2, \ldots, N - 1$.

For simplicity, the window weights are set equal to one, i.e., $w(i) = 1$ for all i.

It can be shown that the components are related by the relationship, $X(k) = X^*(N - k)$, for $k = 0, 1, 2, \ldots, N$, with $X(0) = X(N)$, since $X(0)$ and $X(N)$ are real. The asterisk represents complex conjugate.

If the input data are an additive mixture of signal, noise, and interference of the form,

$$x(i) = s(i) + n(i) + I(i),$$

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then the components in the frequency domain are,

$$X(k) = S(k) + N(k) + I(k).$$

The signal, $s(i)$, which is the information bearing component of the received data, is corrupted by noise, $n(i)$, and interference $I(i)$.

If the interference is narrowband and within the bandwidth of the signal it will generally degrade the autocorrelation estimate of the signal. The approach that will be considered to rectify this problem is to remove the interferring components from the signal by using an INL.

The INL is defined, for complex values, as

$X(k) = \underline{0}$, if $k = kg + md$

$X(k) = \underline{0}$, if $k = N - (kg + md)$

$X(k) = X(k)$, otherwise,

where, $m = 0, 1, 2, \ldots, I - 1$, d = integer constant, and $0 \le kg + md \le N/2$, and $N/2 \le N - (kg + md) \le N$. Here, the symbol, $\underline{0}$, means that both real and imaginary parts are set to zero.

The interferring frequencies start at kg and extend to $kg + (I - 1)d$. In order to include interference that may be periodic in the frequency domain the parameter, d, will not equal one, i.e., $d \ne 1$.

For example 60 Hz interference and its harmonically related frequencies are sometimes present in systems. In this case d may represent the number of frequency bins between components.

Once the inteferring components have been identified and removed by the INL the output is given by

$$Y(k) = X(k) - \sum_{m=0}^{I-1} X(k) \left\{ \delta[k - (kg + md)] \right.$$

$$\left. + \delta[k - N + (kg + md)] \right\} \quad ,$$

where the Kronecker delta function $\delta(k-p)$ is equal to one when $k=p$ and is equal to zero otherwise.

The inverse DFT of $Y(k)$ is

$$y(i) = s(i) + n(i) + I(i) - I_R(i),$$

where,

$$I_R(i) = \sqrt{1/N} \sum_{m=0}^{I-1} \left\{ X(kg + md) \exp[j2\pi i (kg + md)/N] \right.$$

$$\left. + X^*(kg + md) \exp[-j2\pi i (kg + md)/N] \right\} \quad .$$

$A \cdot 1$

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The function $I_R(i)$ can be interpreted as an inverse Fourier transform over the frequencies, kg through kg + (I - 1)d, which are removed from the input x(i).

Therefore, all the frequencies contained in $I_R(i)$ will be removed from x(i). If the signal is separated, in frequency space, from $I_R(i)$, then only the interference and those frequencies of the noise contained in $I_R(i)$ will be removed. However, if part of the signal is contained in the interferring frequency space it will also be removed. This represents a disadvantage of the method. In some applications the partial loss of signal may be tolerated if the overall performance is improved.

The effectiveness of the INL may be measured from the error equation

$$\text{Error} = \overline{s(i)\ I_R(i)} \ / \ \overline{s(i)^2} \quad ,$$

where, s(i), n(i), and I(i) are assumed mutually independent and zero mean processes.

EXAMPLES

1.   Consider a case where the data are two pure sinusoids at two different frequencies. In addition, for the FFT results, assume the frequencies are centered in the frequency bins. One sinusoid represents the signal and the other interference. Therefore, the error will be zero. Figure 2 shows the sum of the two sinusoids in the top graph. The interference is obscuring the signal in the time domain. The bottom graph shows the signal after the interference was removed by the method of using a non-linearity in the frequency domain.

2.   The last example concerns measuring the autocorrelation function of a broadband Gaussian signal. However, a strong additive sinusoid is present in the data. Figure 3 shows the time history of the additive broadband signal and interference in the top graph. The bottom graph represents the time history after the sinusoid has been removed. Since the signal was not completely disjoint from the interference, in frequency space, part of the signal corresponding to the interferring frequency was also removed. Therefore, the error was not zero but, nevertheless, small. The benefit from the method is obvious from the figure. This result is probably appreciated more by observing the difference in the autocorrelation function estimate. Figure 4 represents the autocorrelation function estimate of signal and interference in the top graph. The interference has completely dominated the estimate. The bottom graph shows the same estimate after the interference has been removed.

SUMMARY

An ideal non-linearity was applied in the frequency domain to remove interference from a desired signal. The essential mathematical details of this concept were presented. An error function relationship was defined to measure the effectiveness of the INL concept. Two examples were give to demonsrate the method.

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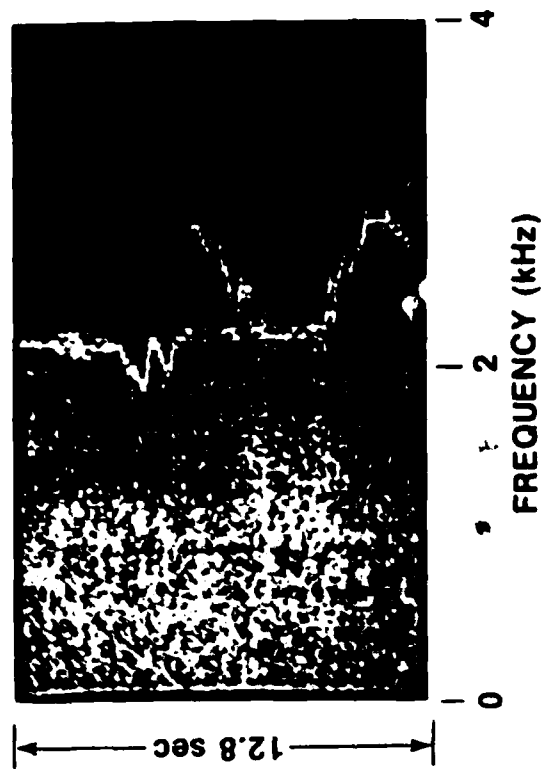
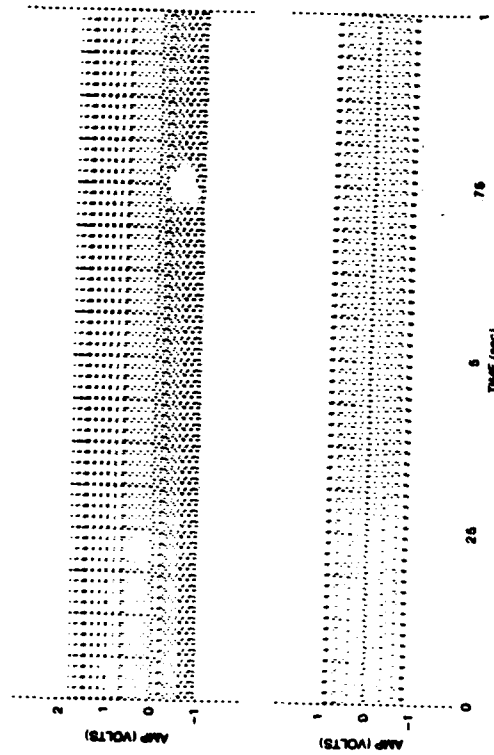Figure 1. Frequency Domain Arctic Narrowband Interference

Figure 2. Sinusoidal Interference: top, interference and signal; bottom, signal after interference was removed by a non-linearity.
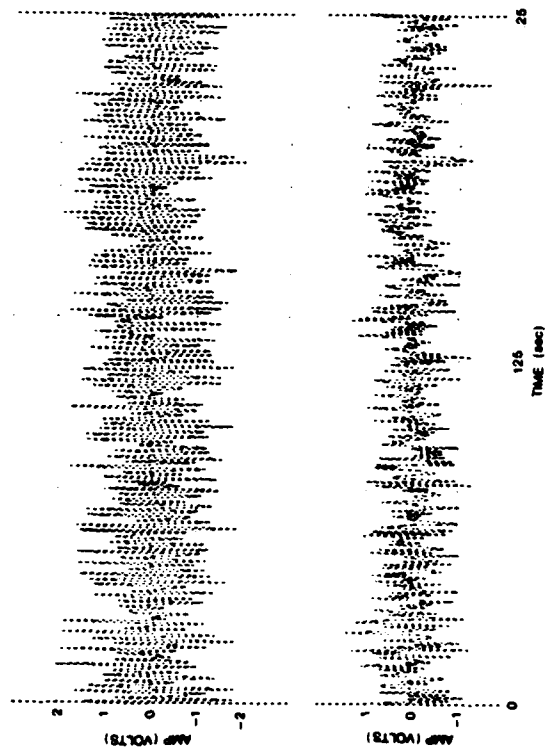
Figure 3. Broadband Signal with Sinusoidal Interference; top, time history of signal and noise; bottom, broadband signal after sinusoid has been removed by a non-linearity.
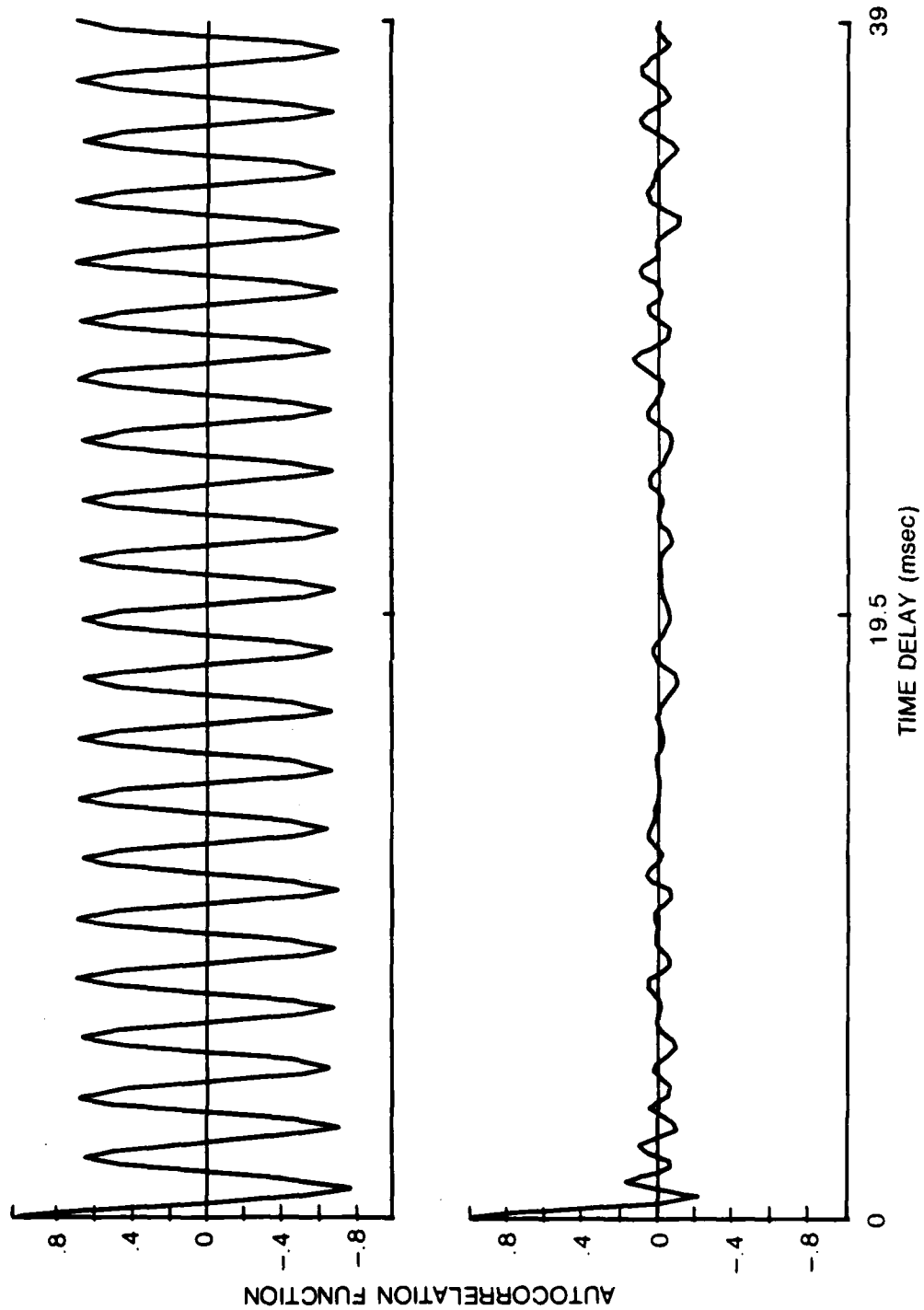
Figure 4. Autocorrelation Function: top, broadband signal and sinusoid; bottom, autocorrelation function of broadband signal after sinusoid has been removed by a non-linearity

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